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Detection of Magnetic Domain Wall in a Permalloy Wire by the Local Hall Effect

Yoshiaki. Sekine[1], Tatsushi. Akazaki[1], Junsaku. Nitta[2,3]

[1]NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation,
3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
[2]Graduate School of Engineering, Tohoku University, 6-6-02 Aoba, Aramaki-aza, Aoba-ku, Sendai, Miyagi 980-8579, Japan
[3]CREST-JST, Japan Science and Technology Agency, 4-1-8 Honchou, Kawaguchi, Saitama 331-0012, Japan

1. Introduction

In the research field of spintronics [1], intensive studies have been carried out on devices controlling the position of a magnetic domain wall (DW) such as a logic device performing NOT-operations [2] and a magnetic race-track memory [3]. In order to investigate a DW position, ferromagnetic wires with a notch or hole structure trapping a DW were fabricated, and the detections of a DW using the giant magnetoresistance [4,5], anisotropic magnetoresistance [6], and extraordinary Hall effect [7] were demonstrated. Comparing with these methods, the local Hall effect (LHE) method [8] has an advantage of high sensitivity enough to measure a DW velocity [9]. In this work, it is demonstrate that the DW trapped in a notch in a permalloy, $Ni_{80}Fe_{20}$, wire is detected by the LHE method and the DW structure is clearly distinguished between a head-to-head and a tail-to-tail DWs.

2. Sample Fabrication and Experimental Method

An InGaAs two-dimensional electron gas (2DEG) with a 2.5-nm-thick InP barrier layer was grown by the molecular-organic-chemical-vapor deposition. A Hall bar with three $0.8 \times 0.8\ \mu m^2$ Hall crosses was fabricated by the electron beam (EB) lithography and electron-cyclotron dry etching. A 60-nm-thick and 300-nm-wide $Ni_{80}Fe_{20}$ wire was deposited on the InP surface layer. A 5-nm-thick gold was deposited on the $Ni_{80}Fe_{20}$ wire for preventing the oxidation of $Ni_{80}Fe_{20}$. The $Ni_{80}Fe_{20}$ wire consisting of a tapered end, a right-angle end, and a centered notch was made by the combination of the EB lithography and lift-off technique. The scanning electron microscopy (SEM) image and the schematic cross view of the sample are shown in figures 1(a) and (b), respectively. Three Hall crosses are just under the tapered end, the notch, and the right-angle end. The stray magnetic field from each region of the magnetic wire is detected by the Hall cross. Using a lock-in-amplifier with a frequency of 172 Hz, the Hall resistivities of the three Hall crosses were measured at 300 K with sweeping an external magnetic field, H_{ex}, parallel both to the wire and to the 2DEG.

The $Ni_{80}Fe_{20}$ wire with these structures results in the nucleation, trapping, and annihilation of a DW at the right-angle end, centered notch, and tapered end, respectively. The magnetization reversal processes and the Hall resistivity, ϱ_{yx}, of three Hall crosses with sweeping H_{ex} are shown schematically in Fig. 2. Here, ϱ_{yx} of the probe at the right-angle end, centered notch, and tapered end are defined as $\varrho_{yx}1$, $\varrho_{yx}2$ and $\varrho_{yx}3$, respectively. Before measurements, H_{ex} was increased over the saturated field of the $Ni_{80}Fe_{20}$ wire, and the situation is shown in Fig. 2(a). With decreasing H_{ex}, the DW nucleates at the right-angle end of the $Ni_{80}Fe_{20}$ wire. The direction of the stray field from the right-angle end changes to the opposite direction due to the nucleation, which results in the sharp jump of $\varrho_{yx}1$. After the nucleation, the DW displaces to the other side of the wire, however, the DW is trapped at the center due to the notch structure as shown in Fig. 2(b). This trapped DW is a head-to-head DW. The stray field of the head-to-head DW results in the dip of $\varrho_{yx}2$. With decreasing H_{ex} furthermore, the DW escapes from the notch, displaces to and annihilates at the tapered end. The direction change of the stray field caused by the annihilation results in the sharp jump of $\varrho_{yx}3$ as shown in Fig. 2(c). Figures 2(d), (e), and (f) show the magnetization reversal processes with increasing H_{ex}. The processes of the nucleation, trapping, and annihilation of the DW are same as the situations with decreasing H_{ex}. However, the trapped DW is a tail-to-tail DW and $\varrho_{yx}2$ shows a peak due to thes-tray field from the tail-to-tail DW. Note that the nucleation occurs at the right-angle end in both cases with decreasing and increasing H_{ex}.

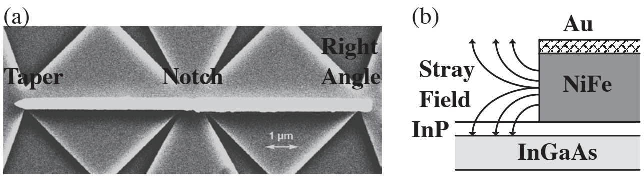

Fig. 1 (a) A SEM image of the sample. Three Hall crosses are just under the tapered end, centered notch, and right-angle end of the $Ni_{80}Fe_{20}$ wire. (b) A schematic view of the sample. An InGaAs 2DEG detects the stray magnetic field from the wire. The sweeping direction of H_{ex} is parallel both to the wire and to the 2DEG.

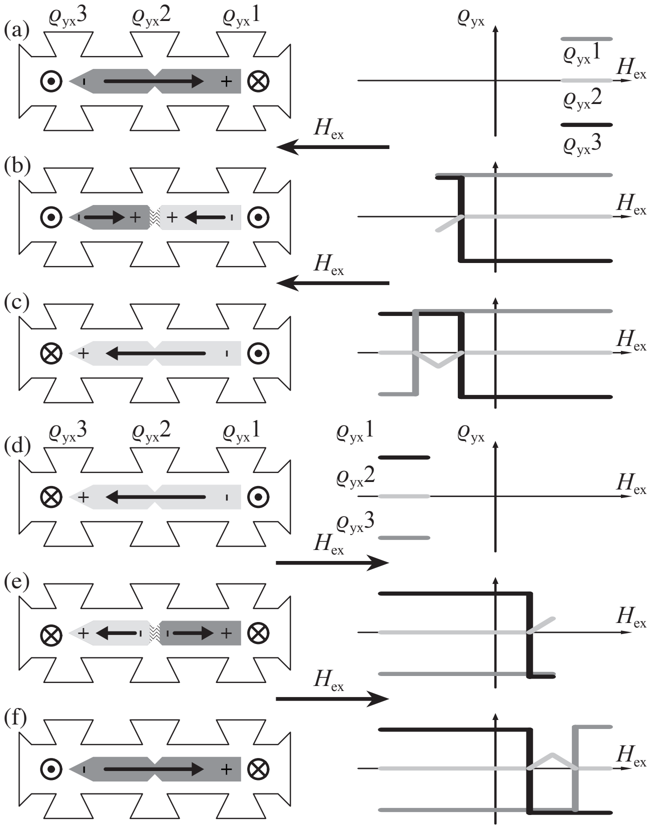

Fig. 2 The magnetization reversal processes. A top view of the sample and the H_{ex} dependences of $\varrho_{yx}1$, 2, and 3 is schematically dipcterd. $\varrho_{yx}1$, 2, and 3 represents ϱ_{yx} on the right-angle end, notch and tapered end, respectively. The DW nucleates at the right-angle end and the head-to-head and tail-to-tail DWs are trapped with decreasing and increasing H_{ex}, respectively.

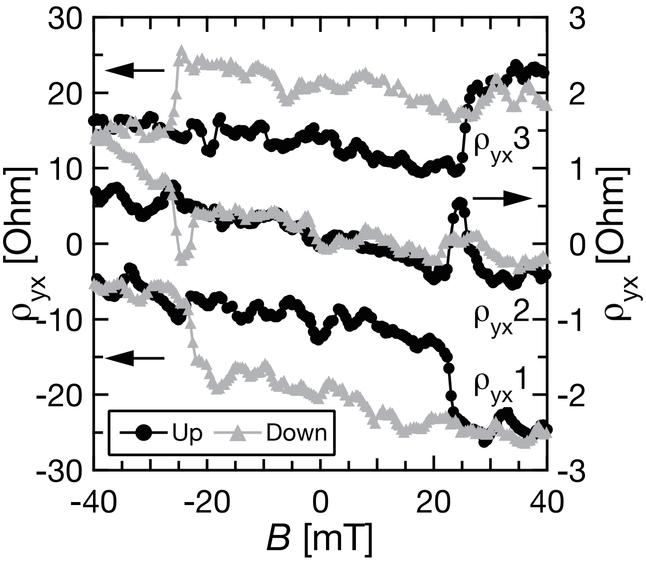

Fig. 3 $\varrho_{yx}1$, 2, and 3 with sweeping H_{ex} measured by a lock-in-amplifier at 300 K. The sharp jumps of $\varrho_{yx}1$ and 3 correspond to the nucleation and annihilation of the DW, respectively. The dip and peak of $\varrho_{yx}2$ with decreasing and increasing H_{ex} show the trapped the head-to-head and tail-to-tail DWs, respectively.

3. Experimental Results and Discussion

Figure 3 shows ϱ_{yx} of three Hall crosses as a function of H_{ex}. The left and right axes represent $\varrho_{yx}1$ or $\varrho_{yx}3$, and $\varrho_{yx}2$, respectively. The scale of left axis ten times as large as that of right axis. Sharp jumps of $\varrho_{yx}1$ and $\varrho_{yx}3$ are observed around the coercive force, and curves of $\varrho_{yx}1$ and $\varrho_{yx}3$ show clear hysteresis loops with sweeping H_{ex}. The sharp jumps correspond to the nucleation or annihilation of the DW, and the directions of the jumps are opposite to each other between $\varrho_{yx}1$ and $\varrho_{yx}3$. These rapid changes are approximately 10 Ω. These sharp jumpsof of $\varrho_{yx}1$ and $\varrho_{yx}3$ occur at ±22 and ±26 mT, respectively. As expected, the DW nucleates at the right-angle end in a lower coercive force of 22 mT, and annihilates at the tapered end in a higher coercive force of 26 mT. Between these two lower and higher coercive forces, $\varrho_{yx}2$ shows a dip with decreasing H_{ex} and a peak with increasing H_{ex}. These dip and peak correspond to the trapped head-to-head and tail-to-tail DWs, respectively. This is because the stray magnetic field from the head-to-head and tail-to-tail DWs are opposite. These results clearly show that the DW can be detected by the LHE method. Moreover, it is possible to investigate an inner DW structure. The peak and dip heights are approximately 1 Ω and this value is one tenth of the sharp jumps of $\varrho_{yx}1$ and $\varrho_{yx}3$. These heights depend on the stray field from the DW. The small changes of $\varrho_{yx}2$ indicate that the trapped DWs have a inner DW structure that reduces the stray magnetic field.

4. Summary

By the LHE method, the DW trapped at the notch in the $Ni_{80}Fe_{20}$ wire was detected and the head-to-head and tail-to-tail DWs were determined from the change of ϱ_{yx}. The LHE method has an advantage of the large signal and makes it possible to investigate the inner DW structure. These results is useful for future DW devices.

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